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The analysis of possible application of different working gases in cold gas spray method: dynamics and temperatures of particles

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The paper analyzes the possibility of application of different working gases and their mixtures in cold gas spraying method (CGSM). The gases such as: (i) H₂O vapors; (ii) CO₂; and (iii) Ar were considered. On the other hand, the analysis included the gas mixtures of Ar, CO₂ and N₂ with H₂O vapor. The temperature of analyzed gases was supposed to be $T=800$ K and its pressure $P=2$ MPa which are the typical values in CGSM. The calculation of the profiles along the convergent-divergent nozzle of gas and particle velocity was carried out with the use of *Fluent* software. The velocity profiles of all analyzed gases were compared to that of the standard gas in CGSM, nitrogen flowing in the same conditions. Finally, the velocities and temperatures of copper particles having diameters 20 and 50 μm in the tested gases flows were calculated and compared to that reached in nitrogen in similar conditions. The difference in temperatures and velocities were explained by sonic velocities, viscosities and thermal conductivities of selected gases.

1 Introduction

The cold gas spray method (CGSM) is one of the newest methods among thermal spraying techniques in which small unmelted powder particles are accelerated in the pressurised gas stream towards the substrate. The bonding is obtained due to excessive plastic deformation which occurs during particles impact. The bonding strength depends strongly on particles velocity which must be above so called *critical velocity* to enable deposition [1]. The rise of the particles velocity is possible by: (i) an increase of the temperature and pressure of the gas; (ii) a modification the nozzle geometry; and, (iii) proper choice of the gas type [2]. The gases used in cold spray process should have high sonic velocity as well as high viscosity in order to transfer efficiently the momentum to powder particles. They should also be cheap, safe and easily available [2]. Currently, nitrogen is very frequently used but when such materials as titanium are processed, the particles velocities do not reach the critical values. Consequently, more expensive gas such as helium must be used. The present paper analyses the possibility of application of gases able to replace helium namely steam, argon, carbon dioxide, as well as their mixtures. Water steam seems to be the most promising candidate as it has high sonic velocity and is cheap as easy accessible. The idea of using water vapor for accelerating particles was already mentioned by Nesterovich et al. [3] but needs more studies verifying usefulness of this gas.

2 Calculation model

The simulation of the gas flow and its interaction with particles was done using commercial software *Fluent* (ANSYS, Fluent Inc., USA). The coupled implicit method was applied to simulate the gas flow. After having obtained the stable solution, the particles were introduced to the gas and their temperatures and velocities were calculating with the discrete phase model (DPM). The gas flow, its turbulent kinetic energy, and turbulent dissipation rate were modelled using second order upwind accuracy [4].

2.1 The computational domain

The calculation axisymmetric area in 2D is shown in the Figure 1. The simulation was performed using convergent-divergent type of nozzle having cylindrical geometry with length of 255 mm and internal diameter at exit I.D.=4 mm. Argon, carbon dioxide, water steam and their mixture with pressure 2 MPa and temperature of 800 K were used as working gases. The powder was fed axially. The atmosphere was simulated as cylinder of 30 mm diameter and 150 mm length starting from the nozzle exit.

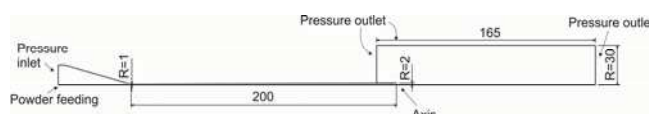


Fig. 1 The computational domain

2.2 The boundary conditions

The stagnation pressure (absolute) at inlet was set to be $P = 2.1$ MPa and the temperature $T = 800$ K. For the exit area the pressure and temperature was 0.1 MPa and 293 K respectively. The nozzle was defined as smooth, not moving boundary without the heat flux with the walls. The gases were assumed to be compressible, viscous, turbulent and obeying the ideal gas laws. The latter is doubtful in the case of steam but as was proved that such assumption is acceptable and gives reasonable results [5-6]. The values of thermal conductivity, specific heat capacity were taken from the *Fluent* database and were assumed to be constant during simulation. The changes in dynamic viscosity with temperature were taken in account using Sutherland formula [7]:

$$\mu = \mu_{ref} \left(\frac{T}{T_{ref}} \right)^{3/2} \frac{T_{ref} + S}{T + S} \quad (1)$$

Where, T_{ref} is reference temperature, μ_{ref} – dynamic viscosity at the T_{ref} , S – Sutherland temperature.

The turbulence of gas was modelled using standard $k-\varepsilon$ model which is computationally efficient and gives

a fairly accurate prediction of the turbulence in the flow of powder particles in the gas stream flowing through the convergent-divergent nozzle [8-10]. The properties of gases mixtures were modelled using gas mixing laws. The molar ratio of gases in mixtures was 1:1.

The spherical copper particles with diameter 20 and 50 μm were used in modelling. The initial velocity was set to 5 m/s and temperature to 300 K.

2.3 Heat and momentum transfer between gas and particles

Particles were modelled as a discrete phase dispersed in a continuous phase and the motion equation was specified using the Lagrange formula [7]. Excluding the gravity force, the balanced of forces acting on a particle is as follows:

$$\frac{du_p}{dt} m_p = F_D \quad (2)$$

where F_D - the drag force, m_p - mass of particle, u_p - particle velocity.

The drag force can be expressed by the following relationship:

$$F_D = \frac{18\mu C_D Re_p}{\rho_p d_p^2} \frac{1}{24} (u_g - u_p) \quad (3)$$

where μ_g - dynamic viscosity of the gas, ρ_p - density of particle, d_p - diameter of particle, C_D - drag coefficient, u_g - gas velocity, u_p - particle velocity, Re_p is the Reynolds number:

$$Re_p = \frac{\rho_p d_p |u_g - u_p|}{\mu_g} \quad (4)$$

In case of spherical particle the drag coefficient was taken from Morsi and Alexander [11]:

$$C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} \quad (5)$$

Where a_1 , a_2 , a_3 are the coefficients applied over several ranges of Re_p .

Since it was assumed that the temperature of particle is below the vaporization temperature and the temperature gradient inside the particle was negligible, the particle temperature during process may be taken as follows [4,7]:

$$\frac{dT_p}{dt} = \frac{h \cdot A_p \cdot (T_e - T_{p0})}{m_p \cdot C_p} \quad (6)$$

where: h - heat transfer coefficient of gas, A_p - outside surface area of a particle T_e - gas temperature at the

nozzle exit, T_{p0} - temperature of powder before introduction to the nozzle, C_p - specific heat of particle.

3 Results and discussion

The velocity profile of water steam and that of sprayed particles are shown in Fig. 2. Fig 3 shows the similar profiles for nitrogen. The temperatures in Fig 4 and Fig 5 respectively.

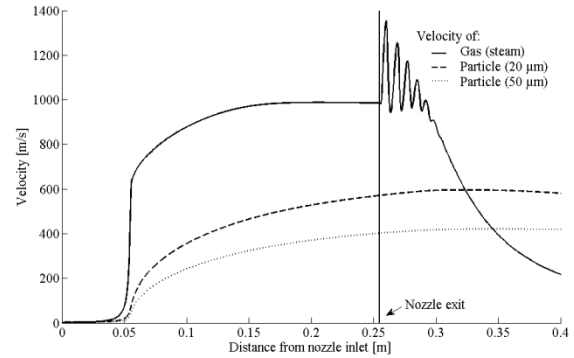


Fig. 2 Profiles of gas and particles velocities in the nozzle axis for steam at 2 MPa and 800 K

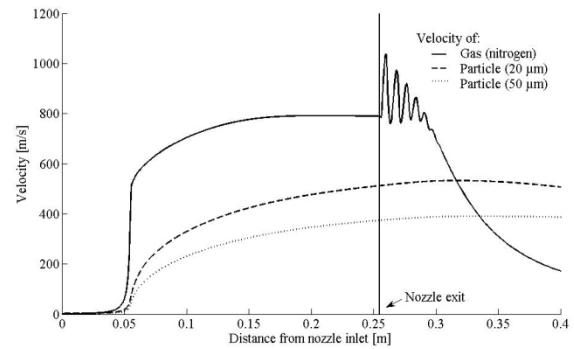


Fig. 3 Profiles of gas and particles velocities in the nozzle axis for nitrogen at 2 MPa and 800 K

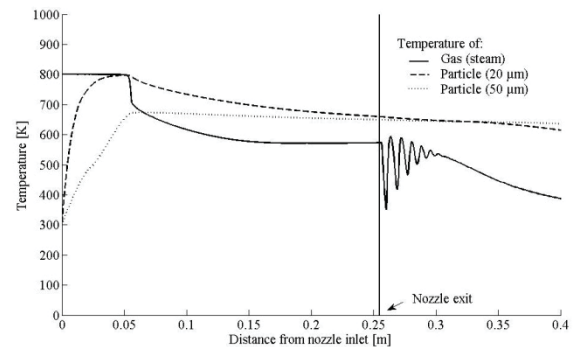


Fig. 4 Profiles of gas and particles temperatures in the nozzle axis for steam at 2 MPa and 800 K

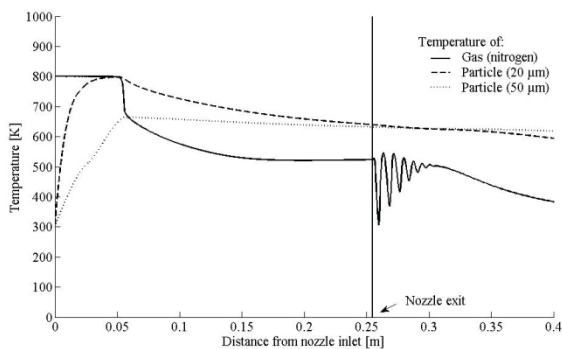


Fig. 5 Profiles of gas and particles temperatures in the nozzle axis for nitrogen at 2 MPa and 800 K

The analyzed copper particles reached on the outlet of the nozzle the velocities which ranged from 402 m/s to 571 m/s in steam and from 374 m/s to 512 m/s in nitrogen depending on their diameter. The both gases accelerated the particles to the greatest velocities and the calculation for argon and carbon dioxide in the same conditions gave the values of 350 m/s to 460 m/s and 341 m/s to 454 m/s respectively (Fig. 6).

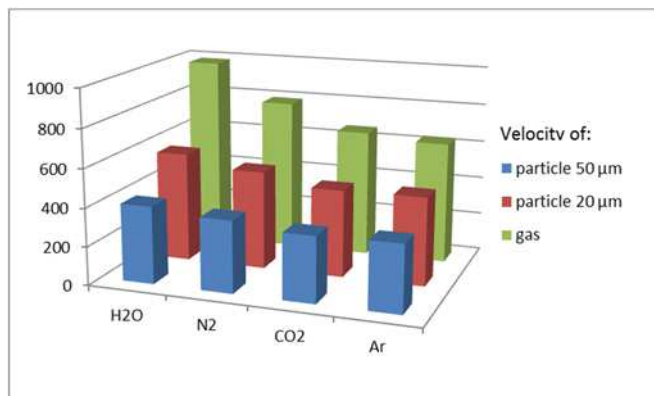


Fig. 6 Comparison of particles velocities at the nozzle outlet for different working gases

The influence of working gas on particle velocity was much clearer for small particles. In case of particle with diameter 50 μm, the velocity in water steam was about 7% greater than in nitrogen. This difference increased to 12 % for 20 μm particles. After leaving the nozzle the particles velocities in water steam and nitrogen are retained and even increased slightly. Outside the nozzle the shockwaves (oscillation of velocities) are visible for all gases. The sharp decline of the gas velocity follows the shockwave.

The acceleration of particles takes place along the nozzle and outside of it. Thus, the highest particle velocity is obtained at the distance of 45 mm from the nozzle exit. The velocity rise is similar for all gasses and equal to about 20 m/s.

The temperature of all gases is similar in the convergent part of nozzle and decreases in its diverging part where the gases decompress. The decompression is the most intensive for argon. This results in the lowest temperature of gas, $T_g = 428$ K and of particles, $T_p = 564$ K to 627 K at the nozzle exit. The decompression is much less intensive for

carbon dioxide. The temperature of this gas in the same position is $T_g = 613$ K and that of particles is $T_p = 641$ K to 709 K (Fig. 7). These temperatures are well below the melting point of copper.

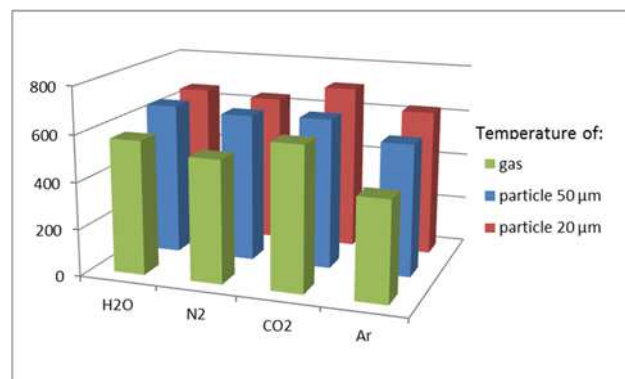


Fig. 7 Comparison of particles temperatures for different working gases at the nozzle exit

The obtained results can be explained by the differences in following gases properties [12]: (i) the ratio of specific heats, γ (ii) the specific gas constant, R (the universal gas constant is divided by the gas molecular weight); and, (iii) dynamic viscosity, μ . The influence of these parameters can be explained using isentropic flow theory. Following this theory, the velocity of gas in the nozzle can be calculated from the following equation [12]:

$$V = M \sqrt{\gamma R T_g} \quad (7)$$

where M – Mach number, γ – specific heat ratio. As the Mach number depends only from nozzle geometry, by constant temperature, the increase of the velocity is possible only by using gas with higher specific heat ratio or specific gas constant. Additionally the dynamic viscosity determines the drag force (see eq. 3-5).

Water steam has the highest specific gas constant and the particles sprayed with have, consequently, the highest gas velocity. On the other hand, smaller dynamic viscosity of this gas in comparison with nitrogen reduces considerably the momentum transfer to sprayed particles.

The particles velocities in these two gases results, therefore, rather from the powder material density and particles size which influence the drag force acting on them as shown in [13]. Consequently, water steam is an efficient working gas to spray light materials having small size.

It should be mentioned that the condensation was not taken into account in used models. On the other hand, the steam would surely transform into water after leaving the nozzle and also on the nozzle walls (to a small degree). It is supposed that this effect would result in an increase of dynamic viscosity and, consequently, in higher particles velocities. However, the further studies are needed to take into account this phenomenon.

The velocity of the powder is important because it influences the coatings' adhesion. Only the particles exceeding *critical velocity*, which is specific for each

material, can be deposited [14]. The critical velocity for copper on copper substrate was found to be 422 ± 45 m/s [15]. Consequently, all tested working gases proved to be sufficient to obtain copper coating. The other important factor influencing the adhesion is particles temperature influencing its thermo-mechanical properties [16].

Many materials, such as metals and alloys, deforms easier in a plastic way with increasing temperature. The cold sprayed powders of such materials deforms at impact with substrate better and their bonding to substrate improves when particles temperatures increases. However this temperature may introduce oxidation what should be avoided when cold spray.

The temperature of the particles may be controlled by the shape of the nozzle by the selection of working gas. Thus, the use of argon, which has high ratio of specific heats, results in particles having much lower temperature than that at spraying with carbon dioxide. The calculated values for $20\ \mu\text{m}$ copper particles are $T_p = 627\ \text{K}$ and $709\ \text{K}$ respectively.

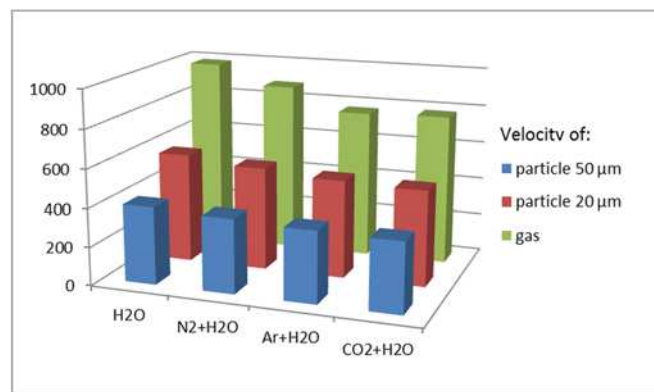


Fig. 7 Comparison of particles velocities for different gases mixtures

The effects the gas mixing on particles velocity is shown in Fig. 7. The calculated particles velocities were lower comparing to that obtained for pure steam. Therefore the pure water steam remains the most interesting potential candidate for working in CGSM. The important residual problem which remains to be solved is the condensation of water on the substrate. One of the solutions is the strong overheating of steam and heating the substrate well above the steam condensation temperature.

4 Conclusions

The paper analyzes possibility of application of different gas for cold gas spray method in comparison to nitrogen, taken as a standard. The temperature and pressure were set as typical value used in this method. The commercial software *Fluent* was used to calculate the velocities and temperatures of particles at processing with different gases. The comparison shows that the highest velocities were obtained for pure steam. The highest temperature were reached by particles sprayed with carbon dioxide and the lowest - with argon. The further work will be carried out to estimate the different effects of steam

condensation on the velocity, temperature of sprayed particles and the quality of obtained coatings.

5 Acknowledgments

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